

Predicting oxygen uptake in older adults using lower-limb accelerometer measures

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Abstract—Assessing physical activity in older adults has proven to be difficult but important, because regular participation has a protective and rehabilitative effect against disability and morbidity. Commercially available physical activity monitors measure waist movements and have not been validated for older adults. This study developed a model for establishing prediction equations to estimate older adults physical activity levels based on lower-limb accelerometer measures. Oxygen uptake and lower-limb accelerometer data were simultaneously recorded from treadmill and stair-climbing exercises. The best stepwise regression equations were obtained when accelerometer and weight measures were regressed on oxygen uptake when subjects walked 1, 2, and 3 miles per hour ($R = 0.69$ with accelerometer on back of the heel) and for accelerometer measures and gender when subjects climbed stairs ($R = 0.77$ with accelerometer on mid-ankle). These findings illustrate that physical activity can be effectively predicted in older adults from lower-limb accelerometer measurements.

Key words: accidental falls, ambulatory monitors, exercise therapy, geriatrics, health promotion, lower limbs, rehabilitation.

INTRODUCTION

Epidemiological studies investigating the effects of physical activity on older adults have shown a protective effect of physical activity participation on disability onset and all causes of mortality [1–2]. Multiple beneficial effects of physical activity on fitness and health include prolonging independence, reducing the risks of developing cardiovascular diseases, and extending the retention

of functional skills. Additionally, physically active persons over 40 years old have reported fewer functional limitations than unfit or sedentary individuals [3–5].

In a longitudinal study of 5,151 subjects, Miller et al. found that over a 6 year period, older adults with varying levels of disability, who reported at least a minimal level of physical activity, experienced a slower progression of functional limitations [6]. The low level of physical activity, through its influence on changes in functional limitations, was shown to slow the progression of disability in activities of daily living (ADLs)/instrumental activities of daily living (IADLs). Consistent with findings in the Miller et al. study, others have found that frequency of physical activity participation was more important than total time spent exercising for reducing disability in older adults [7]. Older cognitively intact and demented adults who experience lower-limb injuries related to falls and

Abbreviations: ADL = activity of daily living, BMI = body mass index, CSA = Computer Science Application, Inc., IADL = instrumental activity of daily living, MET = metabolic equivalent (resting metabolism), $O_{2\text{uptake}}$ = oxygen uptake, OMCT = Orientation-Memory-Concentration Test, SEE = standard error of estimate.

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are transitioning to frailty often receive physician recommendations to initiate or increase physical activity participation [8–10]. Unfortunately, monitoring physical activity initiation and adherence is difficult. Devices that use accelerometry to assess physical activity in younger individuals are readily available. However, almost all are designed for waist measurements of physical activity, are not appropriate for lower-limb assessments, and may not be sensitive enough for older adults, even though the technology appears to be appropriate [11–13]. Sensitivity is a function of the vertical acceleration “threshold” needed to trigger a step response. Since older adults have a slower gait, often walk with a shuffle, and have lower energy expenditures than younger adults, existing monitors may have a flooring effect where sensitivity is lost with faint and/or slow movement patterns [12–14].

Studies assessing physical activity typically require that monitors be stationed on the waist to measure movement patterns [14]. However, theoretical equations (given in the next section) derived from the relationship between limb velocity and body mass indicate that a model can be derived that effectively estimates relative energy expenditure from lower limbs and other body movements. Therefore, this study evaluated a model designed to be used as a basis to develop prediction equations to estimate oxygen uptake ($O_{2\text{uptake}}$) and, subsequently, physical activity participation by older adults, based on lower-limb movements measured by an accelerometer.

METHODS

This study was conducted at the Rehabilitation Research and Development Center gait laboratory in Atlanta, Georgia. A descriptive research design was employed and all subjects received all assessments. All participants obtained physician clearance to participate in the study and were required to sign informed consent forms approved by the institutional review board prior to participating in this study. We derived the equation model for estimating energy expenditure from lower-limb physical activity from relative accelerometer data and statistically compared it with $O_{2\text{uptake}}$ to establish a model for developing prediction equations [15–16]. To this end, we employed the kinematics equation

$$E = \frac{1}{2}mv^2 = \frac{m}{2T} \int_{t_0}^{t_0+T} a^2 dt, \quad (1)$$

where E is energy expended over the measurement interval, m is mass, v is velocity, a is relative acceleration as measured by the accelerometers, dt is the differential of time, T is the measurement time interval, t_0 is the time at the start of the measurement interval, and $t_0 + T$ is the time at the end of the measurement interval. For this study, the time interval (T) of interest was the last 30 s of an exercise trial. This is the time interval over which oxygen consumption had reached a steady state. Given that a was measured as a discrete value every 5 ms, the integral can be replaced with a summation of the a^2 values

$$E = \frac{m}{2T} \sum_{i=1}^n a_i^2 \Delta t = \frac{m \times 0.05}{2 \times 3} \sum_{i=1}^n a_i^2 = \frac{m}{2 \times 6000} \sum_{i=1}^{6000} a_i^2 = \frac{m}{2} \times \overline{a^2}, \quad (2)$$

where E is the relative energy expended, m is mass, T is the measurement time interval (in this case, 30 s), Δt is the time interval between measurements (in this case, 0.05 s), n is the number of recorded values of acceleration over 30 s (in this case, 6,000), a_i is the individual accelerometer measurement, and $\overline{a^2}$ is the average of the squared acceleration measures taken over the 30 s time interval T [15–16].

While **Equation (2)** seems a very straightforward means for calculating energy expended, one variable is not easily determined for most types of human exercises: mass (m). When subjects are walking or climbing stairs, the relative mass that has to be supported and transported is constantly changing, thus m is not the mass of the person, but rather the effective mass (m_{eff}) of the parts of the person that are moving. For walking, the m_{eff} of the parts of the leg and body are actually moving to propel the body forward, as well as slightly up and down. Physiologically, the larger the amount of muscle mass necessary to generate the movement, the greater the energy expenditure needed to complete the task [17]. Because m_{eff} cannot be easily measured and is different for each type of exercise performed, it must be obtained experimentally. Thus, **Equation (2)** was rewritten, replacing m with m_{eff} , giving

$$E_{\text{ex}} = \frac{m_{\text{eff}}}{2} \times \overline{a^2}, \quad (3)$$

where E_{ex} is the estimated relative energy expended for a specific exercise with the use of this equation. Accelerometer measures can be compared with $O_{2\text{uptake}}$, which is directly proportional to energy expended (E), and thus directly proportional to $m_{\text{eff}} \overline{a^2}$, as represented by

$$O_{2\text{uptake}} \propto E \propto m_{\text{eff}} \times \overline{a^2} \propto \overline{a^2}. \quad (4)$$

Because m_{eff} may be different for each type of exercise, it must be determined for each exercise through a calibration procedure in which $O_{2\text{uptake}}$ is statistically compared with $\overline{a^2}$, with participant mass (actually weight) used as a covariate. The resulting regression equation provides the effective mass for each particular exercise performed:

$$O_{2\text{uptake}} = m_{\text{eff}} \overline{a^2} + b, \quad (5)$$

where b is a constant equal to the $O_{2\text{uptake}}$ consumption when the participant is at rest (where $\overline{a^2} = 0$) [15–16]. Other covariates included in this analysis are participant height, age, gender, and Fullerton test scores. These covariates are included to determine the extent to which they may affect energy expenditure for each type of exercise [15].

Subjects

Sixty-eight older community dwelling ambulatory adults (37 males and 31 females) between the ages of 61 and 89 volunteered to participate in this study. Based on published data from previous studies, 68 participants provided a power greater than 0.80 with sensitivity less than one standard deviation [13]. The participants were recruited from the Atlanta Department of Veterans Affairs and the Wesley Woods Geriatric Center subject registry. Inclusion criteria required that the participants, based on a self-reported telephone interview, were ambulatory; did not have medical conditions such as cardiovascular, respiratory, hypertension, or morphological diseases; and were not taking medications that were contraindicated for exercise. The participants needed to have sufficient cardiovascular endurance that would allow them to walk for 9 min on a treadmill or 3 min on a Stairmaster ergometer.

Screening

All volunteers completed a modified five-item Orientation-Memory-Concentration Test (OMCT) [18] and completed a self-reported telephone physical activity questionnaire prior to participation. The modified OMCT was administered over the telephone and was designed to determine, based on self-report, whether the participant's cognitive status (score <7) was acceptable for participating in this study. The information obtained from two questions modified from the Community Health Activities Model Program for Seniors questionnaire [19] was whether they could (1) walk a quarter mile and (2) walk

up 10 stair steps. Individuals who reported that they could not complete the items of the physical activity questionnaire were not included in the study.

Instrumentation and Variables

Six variables were selected from the Fullerton Functional Fitness Test for Older Adults developed by Rikli and Jones [20] to categorize the fitness status of participants into fit and low-fit groups. The variables used in this study are—

- Chair Stand.
- Arm Curl.
- 2 Min Step-in-Place.
- Chair Sit.
- Foot Up-and-Go.
- Back Scratch.

Scores from the individual test items greater than 25 percent were considered fit and scores below 25 percent were classified as low-fit values. Rikli and Jones demonstrated that the test is a tool for measuring functional fitness, which can help prevent or reduce physical frailty and disability [20]. Individuals that scored above 25 percent on the 2 min step test and two of the other five tests were considered fit.

Participants were measured for height, weight, body mass index (BMI), resting heart rate, respiration rates, and blood pressure. An AeroSport KB1-C portable analyzer measured the rate of $O_{2\text{uptake}}$, fraction of expired oxygen, and ventilation in the older adults while they performed the different exercises. We selected the AeroSport portable system because we evaluated other physical activities not included in this study that required freedom of movement and we wanted consistency of measurement. To ensure the accuracy of the AeroSport analyzer, we calibrated it against a Parvomedics metabolic system during rest and at speeds from 1 to 5 mph on the treadmill, both prior to and following this investigation. The correlations for the different variables and speeds ranged from 0.91 to 0.94. Of particular interest was that ventilation had the lowest correlation of 0.91. This lower correlation may be partially due to unusually low ventilation values at rest. The averaged $O_{2\text{uptake}}$ values for the Parvomedics ranged from $0.22 \pm 0.08 \text{ L} \cdot \text{min}^{-1}$ at rest to $2.16 \pm 0.05 \text{ L} \cdot \text{min}^{-1}$ at 5 mph and from $0.20 \pm 0.08 \text{ L} \cdot \text{min}^{-1}$ to $1.92 \pm 0.4 \text{ L} \cdot \text{min}^{-1}$ for the Aerosport analyzer, and no differences existed ($p > 0.05$) between the values at any speed. The validity and reliability of the AeroSport measurements were sufficient (means were

not different, $p > 0.05$ and $r = 0.91$ – 0.94) compared with the Parvomedics metabolic system to warrant its use in this study.

Test Protocol

We used walking and stair-climbing tests in this study to assess the relationship between physical activity and $O_{2\text{uptake}}$. Based on results from the Fullerton Functional Fitness test, we employed two walking protocols (**Table 1**), one for the fit and one for the low-fit participants. The fit protocol required subjects to complete four stages that included walking at speeds of 1, 2, and 3 mph and walking at a 5 percent grade at 2 mph. The low-fit protocol required subjects to complete four stages that included walking at speeds of 1, 1.5, and 2 mph and walking at a 5 percent grade at 1 mph. The first stage was 3 min long and the other three stages were 2 min each. For the Stairmaster climbing test, participants stepped up 8 in. steps for 3 min. The speed at which the participants stepped varied. Speed was determined by the rate at which the participant took the next step. The participants were encouraged to wait until the descending step stopped, but some did not, while others would let the step come to rest and pause for a moment before generating the next step.

$O_{2\text{uptake}}$, heart rate, and $\overline{a^2}$ were measured simultaneously for the duration of the tests. We collected heart rates during both the treadmill and climbing tests to monitor the intensity of the exercise and to help ensure the safety of the participants. Based on heart rate responses for the last 15 s of each minute of the different stages, the participants reached a steady state. During the tests, we also asked participants to provide ratings of perceived exertion, spotted them, and observed them for other signs of undue strain or stress to further ensure their safety. If a participant felt overly fatigued before completing the test, the participant was allowed to discontinue.

Table 1.
Treadmill testing protocol for walking.

Fit				Low-Fit			
Stage	Time (min)	Speed (mph)	Grade (%)	Stage	Time (min)	Speed (mph)	Grade (%)
1	3	1	0	1	3	1	0
2	2	2	0	2	2	1.5	0
3	2	3	0	3	2	2	0
4	2	2	5	4	2	1	5

The accelerometer monitors used in this study were FitSense Technology, Inc., EEM Pro3 (Southborough, MA), designed for lower-limb assessments, with software modification enabling the recording and storage of raw accelerometer output for 15 min. Four accelerometers were placed on the participants, two per leg, per test (heel of shoe, top of shoe, medial ankle, and lateral ankle). Two monitors on the left foot/leg and two on the right foot/leg were employed in a pseudorandom rotational sequence of body locations. These sites were selected because they assess lower-limb movements and they are sites that are more likely to be tolerated by demented older adults. The EEM Pro3 accelerometers contained two-axis acceleration chips, and the amplitude was adjusted to provide full-scale 8-bit conversion of this analog data. While this may have raised the noise level a small amount, we were able to achieve a more precise 8-bit representation of the analog data.

The data obtained from the accelerometers were squared and averaged to produce $\overline{a^2}$, the relative expression used for the accelerometer results in this study.

Data Analysis

We combined the data of the fit ($n = 38$) and low-fit ($n = 30$) participants to increase the generalized value of the findings. Descriptive statistics (means and standard deviations) were computed for all variables. We calculated correlations to determine relationships between $\overline{a^2}$ and $O_{2\text{uptake}}$ for each accelerometer location and the different stages of the testing. Stepwise regression analyses determined the set of variables that best predicted $O_{2\text{uptake}}$ for the different conditions. Acceleration squared, weight, and gender were entered in each of the analyses as independent variables.

RESULTS

Descriptive statistics of the participants are presented in **Table 2**. Based on gender, no differences emerged in BMI or $\overline{a^2}$ response patterns during the walking and stair climbing tests; therefore, data from both men and women are included in the same data analyses. The fitness levels of the participants ranged from low to relatively fit based on results from the Fullerton Functional Fitness Test. Three participants were not able to complete the walking protocol, and their data were not included for that stage of the data analyses.

Table 2.

Physical characteristics of participants.

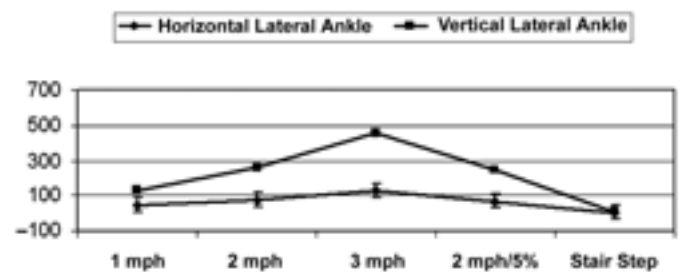
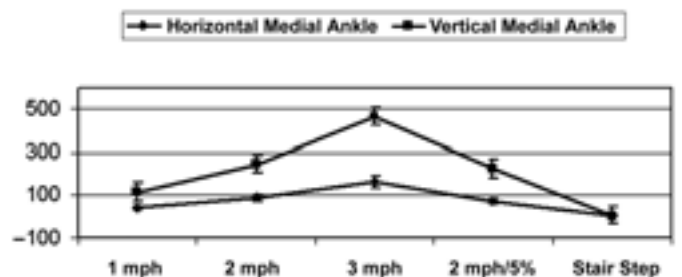
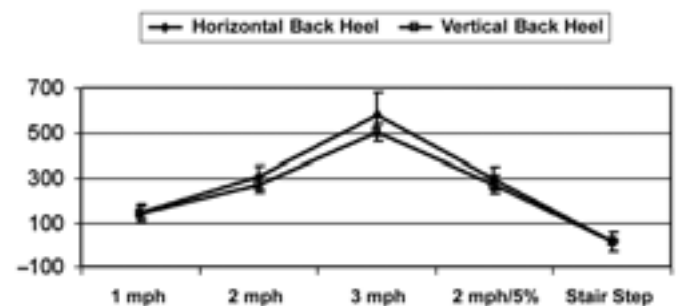
Variable	Males (<i>n</i> = 37) (Mean ± SD)	Females (<i>n</i> = 31) (Mean ± SD)	Total (<i>N</i> = 68) (Mean ± SD)
Age (yr)	72.4 ± 7.2	73.6 ± 6.1	72.9 ± 6.7
Height (cm)	178.8* ± 6.7	164.0* ± 5.4	172.1* ± 9.6
Weight (kg)	86.6* ± 14.3	73.8* ± 13.7	80.7* ± 15.3
BMI (wt·kg/ht·m ²)	27.0 ± 3.8	27.5 ± 5.1	27.2 ± 4.5

*Means are different at *p* < 0.05. SD = standard deviation BMI = body mass index

The results from the accelerometer readings are expressed as average acceleration squared (a^2) in arbitrary units, because the accelerometer was not calibrated for specific units. The responses from the lateral and medial ankles showed that the a^2 increased as the walking speed increased from 1 to 3 mph. When the speed was held at 2 mph and a 5 percent grade added, the a^2 remained at the same level as a simple 2 mph walking speed with no grade. The a^2 values were relatively low when the participants performed stair climbing on the ergometer. The findings regarding graded stage of the treadmill walking test and stair climbing indicate that their relationship with energy expenditure as measured by a^2 is different than walking on level ground. Therefore, different assumptions or assessment equations must be used to effectively estimate energy expenditure or $O_{2\text{uptake}}$ for these activities.

The response patterns for the vertical and horizontal axes on the lateral and medial ankles were different: smaller a^2 values were observed for the horizontal axis (Figures 1 and 2). The lower a^2 values for the horizontal axis suggest the possibility that the accelerometer sensitivity of this axis is less than the vertical axis or that vertical movement requires much greater energy expenditure than horizontal movement when subjects were walking.

The response patterns for the heel and top of the foot were relatively similar and produced a near-linear relationship when a^2 was plotted against walking speeds between 1 and 3 mph (Figures 3 and 4). Similar to the lateral and medial ankle, the linear relationship was lost when the subject's speed was held constant and the 5 percent grade was added, and when subjects walked upstairs on a climber. For the heel and top of the foot, the horizontal and vertical axes responded in a reasonably similar manner as the magnitude of the increase for the two axes when subjects were walking at the respective speeds on level ground.

**Figure 1.**Lateral ankle averaged acceleration squared during exercise (*n* = 65).**Figure 2.**Medial ankle averaged acceleration squared during exercise (*n* = 65).**Figure 3.**Heel averaged acceleration squared during exercise (*n* = 65).

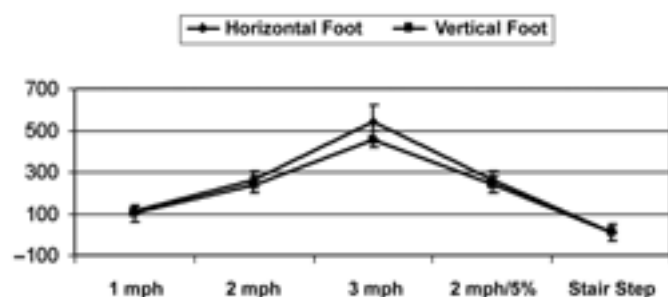


Figure 4.

Top of foot averaged acceleration squared during exercise ($n = 65$).

The response pattern for $O_{2\text{uptake}}$ and walking illustrated in **Figure 5** produced a near-linear relationship between speeds from 1 to 3 mph and for 2 mph and 5 percent grade. The figure indicates that the $O_{2\text{uptake}}$ for the step test was less than for walking at 2 mph and 5 percent grade. Differences in the a^2 response patterns for different exercise modes indicate that physical activity monitors for older adults should be task-specific.

Correlation coefficients were computed for the relationship between the mean $O_{2\text{uptake}}$ of level walking at 1, 2, and 3 mph and a^2 for each monitor placement and both horizontal and vertical axes. The results in **Table 3** show that the highest correlations were moderate, ranging from 0.54 to 0.61, and were for back-heel horizontal and vertical axes and mid-ankle vertical axis. When we averaged and evaluated the $O_{2\text{uptake}}$ for the three walking speeds, walking at 2 mph and 5 percent grade, and stair climbing to determine the relationship with a^2 , the correlations were relatively low (ranging from 0.29 to 0.38) and were smaller than for walking speeds alone. The highest relationship for stair climbing was for mid-ankle placement and was between $O_{2\text{uptake}}$ and a^2 . The correlations for all placements during climbing ranged from 0.24 for back heel to 0.77 for mid-ankle.

The best stepwise regression equation for stair climbing was generated when the $O_{2\text{uptake}}$ was predicted from a^2 and gender (multiple $R = 0.77$); thus, 59 percent of the variance could be explained during climbing (**Table 4**). The monitor placement for this assessment was lateral ankle and in the horizontal axis; we observed an error of estimate of $1.6 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. When $O_{2\text{uptake}}$ was predicted from the mean a^2 of walking 1, 2, and 3 mph and body weight at the back-heel location along the vertical axis, we observed a multiple R of 0.69 that accounted for 48 percent of the variance. We also obtained an effective prediction equation for mid-ankle at the vertical axis; we

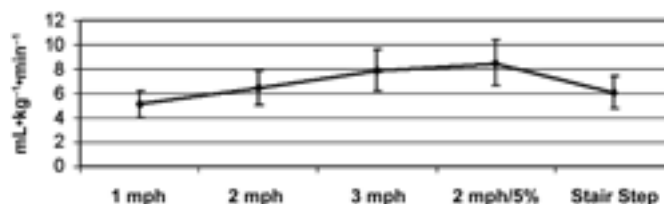


Figure 5.

Oxygen uptake during exercise ($n = 65$).

observed a multiple R of 0.61. These results clearly indicate that values of m_{eff} specific to each physical activity are necessary for the prediction of $O_{2\text{uptake}}$ or energy expenditure for older adults and that their walking gait pattern is best predicted from vertical axis accelerometer measures.

DISCUSSION

This study determined the effectiveness of a model designed to develop prediction equations to estimate $O_{2\text{uptake}}$ and, subsequently, physical activity participation by older adults, based on lower-limb accelerometer and physical characteristics measurements. The equations were based on energy being equal to mass times acceleration squared. As a result, the square of the acceleration in this study should be equivalent to the energy and should correlate with energy expenditure assessed by indirect calorimetry.

The results show that prediction equations based on level walking and stair climbing can effectively estimate $O_{2\text{uptake}}$ in older adults. For the best results, the equations must be task-specific because accelerometers are not effective in distinguishing between physical activities modes. This finding is consistent with results from another study that found that a triaxial Tritrac accelerometer shared a stronger relationship with accelerometer count during walking than during multiple physical activities [12].

Many older adults who have experienced a fall or some other mishap and are rehabilitating from the injury are often encouraged to exercise. Understanding the activity pattern generated by the lower limbs is vital for many older adults, because lower-limb functioning predicts functional decline in community-dwelling older people [21–22]. Having a procedure that can be used to effectively estimate physical activity patterns from the lower limbs can help geriatric healthcare professionals to

Table 3.Relationship between $O_{2\text{uptake}}$ and acceleration squared (\bar{a}^2) for walking and Stairmaster step tests.

Test ($O_{2\text{uptake}}$ [$\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$])	Back Heel X ($\bar{a}^2\cdot\text{min}^{-1}$)*	Back Heel Y ($\bar{a}^2\cdot\text{min}^{-1}$)*	Lateral Ankle X ($\bar{a}^2\cdot\text{min}^{-1}$)*	Lateral Ankle Y ($\bar{a}^2\cdot\text{min}^{-1}$)*	Top Foot X ($\bar{a}^2\cdot\text{min}^{-1}$)*	Top Foot Y ($\bar{a}^2\cdot\text{min}^{-1}$)*	Mid-Ankle X ($\bar{a}^2\cdot\text{min}^{-1}$)*	Mid-Ankle Y ($\bar{a}^2\cdot\text{min}^{-1}$)*
Walking (1, 2, 3 mph) $N = 68$	0.58	0.61	0.19	0.43	0.42	0.50	0.29	0.54
Walk, Grade & Step $n = 65$	0.38	0.38	0.29	0.36	0.29	0.31	0.29	0.36
Stairmaster $n = 65$	0.24	0.05	0.64	0.60	0.38	0.22	0.77	0.19

*Square of arbitrary units for acceleration from the accelerometer ($\bar{a}^2\cdot\text{min}^{-1}$).
 X = x-axis
 Y = y-axis

Table 4.Oxygen uptake predicted from averaged acceleration squared (\bar{a}^2), weight, and gender for older adults.

Variable	Intercept	\bar{a}^2	Weight	Gender	R	R^2	SEE	Significance
Heel Y ($\bar{a}^2\cdot\text{min}^{-1}$)* Walking (1, 2, 3 mph) $N = 68$	6.34	0.0049	0.0445	—	0.69	0.48	1.6	0.000
Mid-Ankle Y ($\bar{a}^2\cdot\text{min}^{-1}$)* Walking (1, 2, 3 mph) $N = 68$	4.64	0.0052	0.0042	—	0.61	0.37	2.1	0.000
Lateral Ankle X ($\bar{a}^2\cdot\text{min}^{-1}$)* \bar{a}^2 & Gender Stairmaster $n = 65$	8.02	0.58	—	-2.48	0.77	0.59	1.6	0.000

*Square of arbitrary units for acceleration from accelerometer ($\bar{a}^2\cdot\text{min}^{-1}$).
 SEE = standard error of estimate
 X = x-axis
 Y = y-axis
 \bar{a}^2 = averaged acceleration squared

better monitor the physical activity patterns of older adults. This technology potentially greatly assist in the rehabilitation of older adults with dementia, because this population tolerates monitoring devices better when they are worn on the ankle and foot.

The placements of the accelerometers, the axis of measurement, and the mode of physical activity have all been shown to influence the relationship between accelerometer data and physical activity [23–25]. Therefore, prediction equations were individually developed for each activity in this study. The equation for walking with the accelerometer placed on the heel produced a multiple R of 0.69 and a standard error of estimate (SEE) of $1.6 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ or 0.45 METs (resting metabolism). When the accelerometer was placed on the mid-ankle, an R of 0.61 with an SEE of 0.6 METs was observed. Multiple R -values of 0.42 for multiple modes of physical activ-

ity were lower than for specific physical activities in the present study. The R of 0.69 in the present study is similar to some R -values and smaller than other R -values in the literature [24,26–27]. The relationships were probably influenced by the accelerometers used in this study, because they were more sensitive to fine movements as we expanded the measurement scale to avoid a flooring effect.

The R -value of 0.69 for the walking equation in this study is similar to the r -values of 0.33 to 0.62, estimating indirect calorimeter from different types of accelerometers with participants similar in age [26]. The R -value in the present study is less than the R -value reported by Hendelman et al., who estimated MET levels from walking and the combined results from golf, household, and outdoor activities with a uniaxial Computer Science Application, Inc. (CSA) accelerometer [12]. They found

correlations of 0.78 and 0.65 for walking and the combined physical activities, respectively, with participants between 30 and 50 years of age. Their findings support the finding from the present study that better predictions result from specific activities as opposed to combined physical activities.

The SEE values for heel placement of 0.45 METs and mid-ankle placement of 0.60 METs in the present study are better than the SEE values 0.87 and 0.96 METs for walking and combined activities, respectively, reported by Hendelman et al. [12]. The SEE values in the present study are also better than mean errors of 0.97 METs for CSA and 0.83 METs for the Caltrac, when energy expenditure was predicted from accelerometers in older adults [26].

Possible reasons why the *R*-values in the present study were smaller than some reported in the literature may be partially related to some factors specific to this study. The accelerometers in other studies have flooring effects and are not sensitive to some movement patterns of older adults [26–27]. The AeroSport KB1-C portable system measurement of low respiratory values was sometimes inconsistent. The modes of exercise and the placement of the monitors may have also influenced the prediction values in this study.

The lower relationship between the accelerometers $\overline{a^2} \cdot \text{min}^{-1}$ and $\text{O}_{2\text{uptake}}$ in this study may be partially explained by the lower-limb placement of the monitors in the present study, because in most previous studies monitors were placed on the waist or hip area [28–31]. Also, the low respiratory values we obtained during rest and exercise for the older adults when we measured $\text{O}_{2\text{uptake}}$ may also have contributed to lower relationships. When the AeroSport was compared with the Parvomedics metabolic cart, low respiration was observed for both systems. Since older adults have lower metabolic levels compared with younger adults, the low respiratory values in this study may be reflecting this difference.

Generally, the vertical axis was more responsive to motion than the horizontal axis. Additionally, the accelerometer experienced higher correlations with $\text{O}_{2\text{uptake}}$ when it was placed on the heel and mid-ankle than on the lateral ankle and top of the shoe in the older adults during level walking. This may have been due to the movement pattern of the older adults or the nature of the accelerometer used in this study [24,26].

CONCLUSIONS

In summary, these findings indicate that physical activity levels can be effectively predicted in older adults with the use of accelerometers on lower-limb sites. These results indicate that prediction equations for older adults, based on lower-limb placements, are better when task-specific physical activity equations are developed. Better predictions are obtained for walking when the accelerometer is placed on either the heel or mid-ankle and the vertical axis is selected. The best prediction equation for climbing is obtained on the lateral ankle from the horizontal axis. The sensitivity or accuracy of the prediction equation is decreased when multiple modes of physical activities are used for prediction. The *R*-values found for older adults are not as strong as those observed in many studies with younger participants, but the errors of estimates are similar or smaller. Although these results indicate that healthcare professionals can effectively monitor physical activity in older adults using accelerometers on lower limbs adjusted for greater sensitivity, further research is needed to validate these findings.

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